

Perovskite Solar Cells: In-Orbit Assessment

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Abstract—The increasing demand for long-duration and cost-efficient small satellite missions is driving the need for power technologies beyond conventional silicon photovoltaics. Perovskite solar cells (PSCs) offer high specific power and mechanical flexibility. Notably, recent terrestrial studies on PSCs have demonstrated promising self-healing properties under controlled bias. However, their behaviour under space conditions remains largely unverified. This paper presents a dedicated in-orbit experimental concept focused on the electrical characterisation of PSCs using a purpose-designed data acquisition system (DAQ) tailored for CubeSat integration. The experiment is implemented as part of the 1U CubeSat HEALIOS mission, which is currently under design. The proposed mission architecture treats PSCs as an experimental Payload electrically decoupled from the satellite power bus. During orbital illumination phases, the Payload is operated in nominal photovoltaic mode and characterised as a potential spacecraft power source through maximum power point tracking (MPPT) and current–voltage measurements. During orbital eclipse phases, the experiment transitions to controlled reverse-bias operation to activate and assess self-healing mechanisms within the perovskite material. The developed DAQ autonomously manages the operational modes, enabling direct comparison between PSCs operated in nominal and recovery modes, while simultaneously benchmarking performance against reference silicon cells under identical constraints. This capability is achieved by integrating low-noise power conditioning, independent electronic loading for each solar cell, and synchronised environmental sensing within the DAQ. The mission aims to quantify the in-orbit degradation of PSCs through continuous monitoring of key electrical parameters and evaluation of electrically induced self-healing. Parallel operation with conventional silicon cells under identical orbital conditions enables assessment of relative degradation rates. In-orbit results are compared with terrestrial studies to validate perovskite performance trends. The results aim to provide actionable data to support informed adoption of next-generation power technologies within the SmallSat community and future technology demonstration missions.

Index Terms—perovskite solar cells, CubeSat, HEALIOS, data acquisition system, MPPT, self-healing, in-orbit experiment

I. INTRODUCTION

The number of CubeSat launches into Low Earth Orbit (LEO) has increased in recent years [1], along with more ambitious and power-demanding objectives [2, 3]. Nevertheless, maintaining the long-term reliability of electrical power systems (EPS) to support these advanced Payloads remains a significant challenge. A recent study [4] compared degradation rates for solar panels of nanosatellites during the first operational year in LEO. While enhanced protection reduces the degradation to less than 5%, the results suggest that other photovoltaic solutions lose more than 12% of their power output [4]. Moreover, as reported by Kim et al. [5], EPS problems account for over 25% of all space system failures, a significant portion of which are during the solar array operations.

Within this context, the proposed CubeSat mission aims to demonstrate that applying a short external electrical bias during the eclipse phase can improve the recovery performance of perovskite solar cells (PSCs) [6]. PSCs are photovoltaic devices that use a material with the ABX_3 structure as the light-absorbing layer (A is a large cation, B is a metal cation, X is a halide) [7]. Notably, CubeSats in LEO experience rapid light-dark cycles as they orbit Earth, so such protocols can be applied to their operations.

MISSE-13 is a 10-month mission sent to ISS in 2020 with the goal of testing the viability and durability of metal halide perovskite thin films in a LEO environment [8]. Next, launched from ISS in 2024, Big Red Sat-1 is a 1U CubeSat designed to characterize the in-orbit performance, including the degradation, of three different perovskite solar cell architectures [9]. Similarly deployed from ISS, RHOK-SAT was set to characterise the performance and degradation of PSCs [10]. While these missions did not include specific treatment, the data still allow analysis of the self-healing properties of PSCs. Further, the PoliSpace 6S CubeSat is a 1U CubeSat to characterise various perovskite solar cells over a 1-year mission; in 2023, the project was in Phase C. The satellite includes a dedicated self-healing test board, but there is no application of a negative reverse bias [11]. The HEALIOS mission aims to build on prior developments by leveraging reverse-bias protocols, as demonstrated in studies such as [6], to enhance the self-healing capabilities of PSCs. These are used as solar panels, rather than as a Payload.

II. MISSION DEFINITION

A. Mission Overview

The HEALIOS mission is conducted by students from the Engineering and Management of Space Systems programme, a collaboration between two universities: Hochschule Bremen – City University of Applied Sciences in Germany and Gdańsk University of Technology in Poland. The mission is specifically designed to apply to the ESA Academy’s Fly Your Satellite! programme, taking advantage of its test opportunities. HEALIOS is a scientific satellite mission developed by students to validate the self-healing capabilities of perovskite solar cells under space conditions. The satellite is designed to last at least a year in Low Earth Orbit. As of early 2026, the project is progressing through Phase B.

The mission delivers a 1U CubeSat platform with an in-house designed Payload hosting three types of solar cells: (1) standard silicon solar cells under nominal operation, (2) perovskite solar cells under self-healing operation, and (3) perovskite solar cells under nominal operation. Under sunlight illumination, all solar cells will operate in nominal mode. During the orbital eclipse phase, the self-healing perovskite solar cells will be subjected to a controlled reverse voltage to induce defect passivation. The other solar cells remain passive during that time. After this phase, the performance of the solar cells will be recorded. This process enables quantification of degradation rates for each type of solar cell. It also validates the self-healing behaviour of perovskite solar cells and benchmarks their performance over time against silicon cells and terrestrial ageing data.

The satellite outline is shown in Fig. 1, with the solar arrays inspired by the DMSA provided by the Ecuadorian Civilian Space Agency [12]. With a 20% margin, its total mass is 1.82 kg, and the energy generated per orbit is 3.92 Wh. The Payload consists of perovskite solar cells. These experimental cells are mounted on the satellite face nominally pointing toward the Sun, while two deployable solar arrays are mounted on the other two sides. The face opposite the Payload is for the UHF Transceiver unit, while the remaining ones are dedicated to radiators.

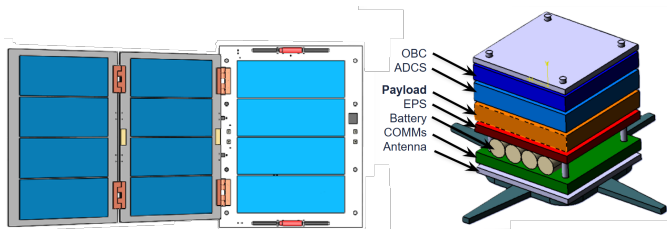


Fig. 1: Configuration overview of HEALIOS CubeSat.

Table 1 summarises the objectives of the HEALIOS mission. A set of parameters is gathered to facilitate the mission; a detailed description can be found in [13, 14]. The first key parameter is the open-circuit voltage (V_{OC}),

the maximum voltage a solar cell can produce when no current is flowing. Analogously, the short-circuit current (I_{SC}) is the current flowing through the solar cell when the voltage across it approaches zero. The maximum power point (MPP , P_{MAX}) is the point on the power curve where the solar cell produces its highest power output. These parameters have been shown in Fig. 2, with the details discussed in [14].

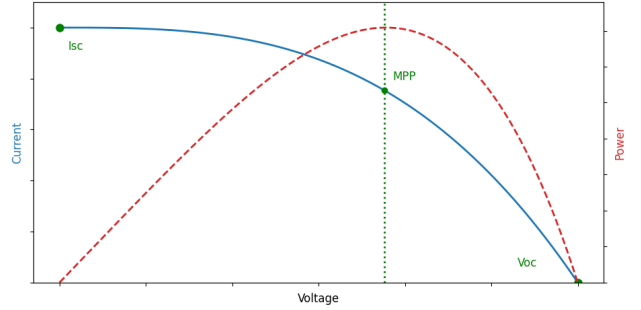


Fig. 2: Sample current–voltage and power–voltage characteristics of a solar cell.

Additionally, several variables are used when analysing the data. The fill factor (FF), which quantifies how efficiently the solar cell converts solar energy into usable power, is defined as the ratio of the maximum power output to the product of the open-circuit voltage and the short-circuit current. Next, the power–time curve represents the temporal evolution of a solar cell’s power output under specified illumination and environmental conditions. To generate this curve, the system records the maximum power point (MPP) at regular time intervals. Finally, the relative degradation rate (DR) quantifies the percentage loss in power output over a specified time interval, relative to an initial reference value. The reference power is measured right after the solar array deployment.

Table 1: Scientific objectives of the HEALIOS mission.

ID	Objective Description
O.1	Primary Objective. Quantify degradation of perovskite solar cells in the space environment by monitoring key environmental and electrical parameters: <ul style="list-style-type: none"> a. open-circuit voltage, b. short-circuit current, c. maximum power output from MPPT algorithm, d. angle of incidence for solar panels.
O.2	Primary Objective. Investigate the self-healing behaviour of perovskite solar cells induced by reverse voltage during orbital eclipse by evaluating I–V characteristics and $MPP(t)$ curves.
O.3	Secondary Objective. Compare degradation rates between perovskite and silicon solar cells by analysing I–V and $MPP(t)$ curves under equal space environment exposure.
O.4	Secondary Objective. Correlate on-orbit perovskite degradation and self-healing results with terrestrial data and literature.

B. Concept of Operations

The operational cycle in orbit is divided into two primary phases. During the Sun Phase (Nominal Sun Mode), all solar cells operate in nominal mode under sunlight illumination. The satellite utilises this time to charge its batteries, exchange telemetry and telecommands with the Ground Segment, and prepare for the upcoming experimental phase. The core scientific experiment occurs during the Eclipse Phase (Nominal Eclipse Mode). A controlled reverse voltage is applied to the specific self-healing perovskite cells to induce defect passivation. Simultaneously, the system performs measurements and stores the resulting data for later downlink. The data collected enable the mission to quantify degradation rates and investigate self-healing behaviour by comparing I-V and MPP(t) curves with those of standard silicon cells and terrestrial data.

Fig. 3 has been prepared to describe all the mission phases since the Launch and Deployment phase. The subsequent Commissioning phase sequentially activates subsystems until ground contact is confirmed. The mission then enters Nominal Operations, cycling between Operational Mode for science data acquisition in sunlight and Idle Mode for perovskite self-healing experiments during eclipse. Underlying all activities, Safe Mode provides continuous autonomous protection against system anomalies.

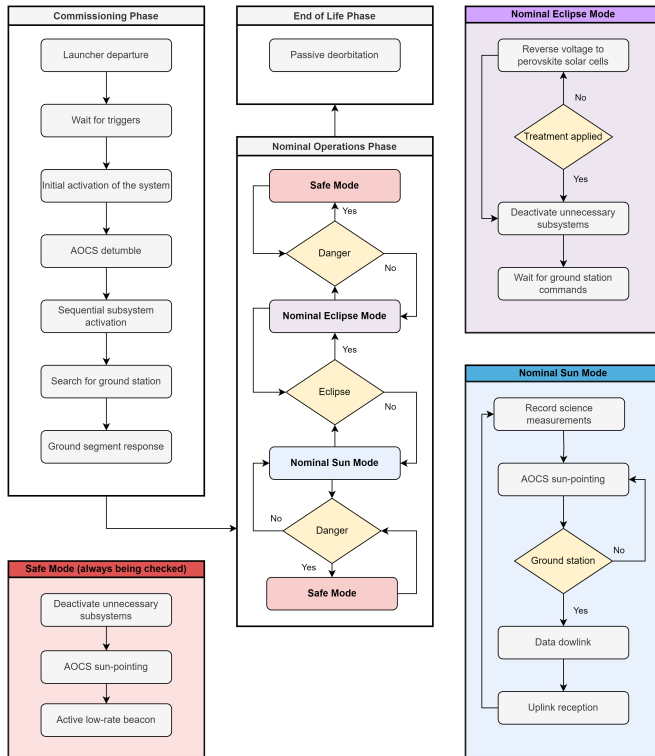


Fig. 3: Major activities of the HEALIOS mission during each phase after the launch.

Figure 4 presents a high-level mission concept organised around two main elements: the perovskite solar cell experiment and the associated data lifecycle. The experiment, which investigates the self-healing behaviour of perovskite solar cells under reverse bias, is described in detail in subsequent sections. A key operational constraint is that the experiment must be conducted during eclipse conditions to ensure consistency with terrestrial studies, such as [6]. As a result, experiment execution is prioritised over the allocation of communication power during these periods. The explanation for this decision is that the data generated by the experiment consists of discrete numerical measurements rather than high-volume imagery. This results in a relatively low data rate and a sufficiently large on-board storage margin, eliminating concerns regarding data capacity or handling.

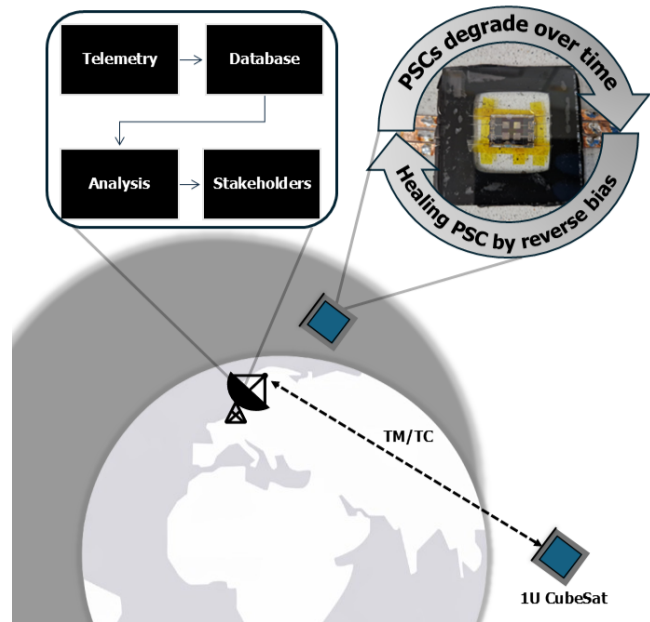


Fig. 4: Concept of Operations for HEALIOS mission.

Staying within the scope of mission data, its lifecycle can be summarised in four main steps, as illustrated in Figure 4. First, telemetry acquired during the mission is received and processed at the mission control centre, where it is stored in a local database. Next, the raw data is transformed into structured, accessible datasets that are easier to analyse and use; these datasets are intended to be open-source. In the subsequent stage, the processed data supports the preparation of technical reports as well as conference and journal publications. While this work is primarily carried out by the internal team, the datasets remain available to the wider scientific community. Finally, these outputs and other supporting data are distributed to relevant stakeholders, particularly to collaborating universities and institutions involved in perovskite solar cells research and manufacturing.

III. PAYLOAD DESIGN

A. Design Drivers and Requirements

The HEALIOS mission is built around validating the self-healing properties of PSCs in space, after promising laboratory results. The overview of the primary mission objective is provided in Table 1. To facilitate this experiment, the HEALIOS Payload consists of a photovoltaic module (PV Module) and a data acquisition system (DAQ Module). In addition to the mission’s scientific objectives, system-level constraints and the environmental conditions associated with LEO are evaluated. Based on the identified drivers, the high-level Payload requirements in Table 2 are derived with the main verification method (Test, Review, Inspection, Analysis). Notably, the Requirements Specification document includes all Payload and lower-level requirements with justifications.

Table 2: Payload requirements and verification methods.

ID	Requirement Description	V.
1.a	The Payload shall provide a module with silicon solar cells operating under nominal conditions.	R I
1.b	The Payload shall provide a module with perovskite solar cells operating under nominal conditions (without any self-healing treatment).	R I
1.c	The Payload shall provide a dedicated module with perovskite solar cells capable of operating under controlled self-healing conditions.	R I
2.a	The Payload shall measure the open-circuit voltage of solar cell modules.	T
2.b	The Payload shall measure the short-circuit current of solar cell modules.	T
2.c	The Payload shall measure the maximum power output of solar cell modules.	T
2.d	The Payload shall support measurement of environmental parameters: temperature, solar irradiance, radiation exposure, and angle of incidence.	T
3	The Payload shall be able to apply a -0.5 V reverse-bias voltage to specified samples once per orbit.	T
4	The Payload shall enable timestamping of all acquired data by the on-board computer.	T
5.a	The Payload shall connect to the electrical power system using the specified interface.	R I T
5.b	The Payload shall communicate with the on-board computer using the specified data interface.	R I T
5.c	The Payload shall integrate mechanically with the CubeSat structure using the specified interface.	R I T
6	The Payload shall be mounted on a CubeSat wall for exposure to the space environment.	R I
7	The Payload shall output data according to the predefined packet structure.	R T
8.a	In Data Acquisition Mode, the Payload shall collect data at designated frequencies.	T
8.b	In OFF Mode, the Payload shall suspend all data collection and transmission.	T
8.c	The Payload shall remain in OFF Mode during the whole duration of launch.	T
9	The Payload shall include at least 16 silicon and perovskite samples for statistical analysis.	R
10	The Payload shall be able to operate for a minimum duration of 12 months.	A T

The first set of requirements (IDs: 1.a, 1.b, and 1.c) defines the experimental samples included in the Payload. A silicon-based PV module serves as a baseline, while perovskite solar cells are divided into groups operating either under nominal conditions or under induced controlled self-healing conditions during the eclipses. The second set of requirements (IDs: 2.a, 2.b, 2.c, and 2.d) defines the measured quantities. The primary electrical parameters are open-circuit voltage, short-circuit current, and maximum power output, as acquired by the MPPT algorithm. The I–V characteristics and the evolution of maximum power over the mission lifetime will be subsequently derived from the acquired data. The context of these mission products is provided by key environmental quantities: temperature, solar irradiance, radiation exposure, and angle of incidence. These measurements are provided by multiple subsystems across the satellite, but the Payload team is responsible for integrating them and ensuring a reliable data lifecycle.

The third requirement (ID: 3) specifies the experiment procedures capability, while the following one (ID: 4) necessitates the timestamping. Importantly, these requirements are supported by the team designing the On-Board Data Handling (OBDH) and are related to the operations of the On-Board Computer (OBC). The next set (IDs: 5.a, 5.b, and 5.c) points to the need to integrate the Payload into the system. Key considerations are data, electrical and mechanical interfaces, which are further defined in the dedicated Interface Control Document (ICD). Furthermore, mounting the Payload on the external CubeSat wall ensures direct exposure to the space environment, reflecting realistic operating conditions of photovoltaic systems and enabling performance validation (ID: 6). The seventh requirement (ID: 7) concerns data formatting. Although supported by the OBDH team, it remains a necessary element of the Payload design.

Subsequently, the set of requirements defining the Payload modes is presented (IDs: 8.a, 8.b, and 8.c). These requirements specify the operational states, including data acquisition and an OFF mode. Lastly, the minimal number of test samples per PV type (ID: 9) and the 12-month mission lifetime (ID: 10) are defined. Together, these 10 main groups of Payload requirements enable data acquisition and transmission, supporting multi-variable analysis and allowing degradation mechanisms observed in orbit to be compared with terrestrial experiments.

It is critical to note that these requirements are pre-selected and simplified to facilitate an overview of the Payload design presented in this paper. They exist within the space of a higher-level set of requirements, which are system-level considerations. Parameters such as mass or power budgets are taken into account. The Payload shall therefore be power-efficient and relatively light, as HEALIOS CubeSat is constrained to weigh less than 2 kg and, in nominal operations, generate around 3.92 Wh of energy per orbit.

B. Payload Architecture

Based on the specified requirements, the Payload is designed as a dedicated composite system with functionally integrated, but physically separated modules. Such architecture provides a clearer division of responsibilities and supports the verification process. The Payload is implemented as two main modules:

- **PV module:** providing the main point of interest in the form of PSCs and reference solar cells mounted on a dedicated extension plate directly exposed to the space environment,
- **DAQ module:** consisting of supporting measurement equipment mounted on the extension plate and control hardware integrated within the spacecraft PCB stack, responsible for taking and handling measurements, as well as functional control.

During science operations, the photovoltaic module is mounted on the face of the satellite and is nominally oriented towards the Sun. This ensures continuous exposure to the solar spectrum. Moreover, it consists of three groups of photovoltaic samples: perovskite solar cells operating in nominal mode, perovskite solar cells operating in self-healing mode, and silicon solar cells serving as a reference. Notably, the PV module does not impose the reverse-bias voltage; it is applied to it by the DAQ module.

The DAQ module can be considered a dedicated interface between the photovoltaic module and the spacecraft. It is realised as a PCB integrated within the internal PCB stack, compliant with the CubeSat PC-104 form factor. Electrical harnessing connects the external photovoltaic module to the DAQ board through dedicated routing paths within the structure. The same method is used to connect outer DAQ module sensors to the microcontroller unit (MCU) and power. Each solar cell is connected to an independent MPPT channel, enabling parallelised and high-fidelity measurements. All the signals are then processed by the MCU and sent to the on-board data handling system as packets. Two dedicated modes are supported, which align with mission modes, presented in Fig. 3:

- **Data Acquisition Mode**
 - **Nominal Sun Mode:** The cells are controlled by MPPT units, and the system continuously acquires V_{OC} , I_{SC} , and P_{MAX} while reconstructing the I–V curve. All scientific data are measured.
 - **Nominal Eclipse Mode:** Half of the PSC samples are subjected to an externally applied, controlled reverse-bias voltage. Operation is restricted to eclipse phases, and voltage and current limits are enforced to prevent irreversible damage. The remaining Payload solar cells remain passive.
- **OFF Mode**
 - During Safe Mode and launch, no scientific data are measured, and no power is supplied to the Payload. The DAQ module waits for OBDH commands before entering Data Acquisition Mode.

C. Measurement Methodology

The measurement concept is not limited to sensing; it comprises a system chain that includes photovoltaic measurements of electrical quantities, environmental sensors, and initial data processing. The methodology distinguishes between two categories of measured parameters. The first being electrical quantities specified by:

- Open-circuit voltage (V_{OC}),
- Short-circuit current (I_{SC}),
- Maximum power point (P_{MAX}).
- Full I–V characteristics.

These parameters directly define the photovoltaic performance and are used to later derive: power–time evolution $P_{MAX}(t)$, Fill Factor (FF) and Relative Degradation Rate (DR). Gathered data could be deemed incomplete without the context of its acquisition. Consequently, the other category relates to environmental quantities required to place the measurements in a context suitable for modelling and reproducibility:

- Temperature,
- Solar irradiance,
- Radiation exposure,
- Angle of incidence.

The measurement sequence is synchronised with the orbital cycle. During Sun illumination, all Payload cells operate continuously under MPPT control. Periodic P_{MAX} logging is taken and processed. I–V sweeps are scheduled in order to enable characterisation of cells. Simultaneously, all sensors are in operation, and environmental parameters are being acquired. When the satellite is in Earth’s shadow and enters Nominal Eclipse Mode, the DAQ module initiates reverse-bias operations. For the photovoltaic module, this means applying a negative voltage to a single row of PSC plates. That implies continuous monitoring of current and voltage. Their limitation is important as PSCs need to remain intact for the whole mission duration. Although the solar cells are not illuminated during an eclipse, voltage and current are sampled at 10 Hz to maintain data continuity. Simultaneously, all sensors are in operation, and environmental parameters are being acquired. It is important to note that sensors measuring properties of the Sun’s environment may produce false or biased readings in this mode. If the satellite switches to Safe Mode, the DAQ module automatically stops all data acquisition and processing. The MCU proceeds into stand-by mode.

All acquired data is time-tagged and synchronised within the DAQ module. Environmental conditions are always recorded alongside electrical data and packed. This enables ready packets to be passed to the on-board data-handling system, primarily the on-board computer. To ensure repeatability throughout the mission lifetime, identical sequences are applied to all cell groups. Naturally, both PSC and silicon solar cells are measured under the same conditions to establish a baseline for comparison.

IV. SYSTEM IMPLEMENTATION

A. Model-Driven Framework

Throughout the design process, the HEALIOS team aimed to establish a reliable single source of truth for system definition and development. To eliminate design gaps and reduce inconsistencies across subsystems, the HEALIOS team adopted a Model-Based Systems Engineering (MBSE) methodology in Phase B of the mission. As a driving framework behind this transition, SysML v2 was selected as the primary modelling language, with its definitions and guidelines provided in [15].

SysML v2 provides semantic precision, improved modularity, and improved integration capabilities compared to both its predecessor and traditional document-based approaches. Unlike static documentation, which is prone to inconsistencies and versioning issues, the model is easily manageable with multiple existing tools and can be shaped to meet the needs.

Table 3: SysML v2 library packages.

Name	Package Description
<i>Electrical-Components</i>	Describes electrical elements such as power buses, signal lines, and interfaces. Provides abstract definitions of electrical elements. Those can be reused to define any lower-level components as inherited components.
<i>Components</i>	Defines the fundamental structural building blocks which serve general functions and are indirectly connected to DAQ. Can be extended with any high-level components that do not contribute directly to DAQ but still serve as its integral part.
<i>Environmental-Conditions</i>	Represents external environmental factors such as radiation, temperature, and solar exposure. Provides operational context and enables interaction with the space environment, both of which are critical for the measurements taken.
<i>PayloadActions</i>	Captures system behaviour, including data acquisition processes, control logic, and operational sequences. Helps to capture traceability between system functionality and mission requirements. It is the source of truth for reusable action definitions.
<i>Data-Acquisition-Module</i>	Defines DAQ module structure and functional decomposition. Encapsulates the module but exposes the necessary interfaces. The usage of actions supports the automation of validation and verification activities.
<i>Photovoltaic-Module</i>	Defines photovoltaic module structure and functional decomposition. Encapsulates the module but exposes the necessary interfaces. Can be connected to the DAQ module by the same interfaces.
<i>Requirements</i>	Defines all of the requirements. Provides a baseline for verification. References components and actions from other packages and connects them to the requirements they fulfill.
<i>Initialisation</i>	Invokes high-level definitions as an example usage of the packages. Allows the whole system to be treated as a black-box, at the same time enabling decomposition to the single part level, depending on intentions.

Within the scope of this work, a dedicated SysML v2 library was developed for the HEALIOS Payload. This library provides a reusable, self-contained system definition, allowing the Payload to be treated as a black-box component that can be readily integrated into larger MBSE-driven projects. The level of abstraction can be intentionally aligned with system engineering needs. Depending on how deeply the project needs to be adapted, one can use the model without the need to go into technical details. On the other hand, low-level details can also be processed easily without any significant loss of the system's cohesion.

Several modelling conventions and best practices have been identified and adopted in the project to ensure clarity and consistency:

- **Strict modularisation** – each package has a separate scope and responsibility.
- **Explicit interface definition** – all interactions between components are modelled using interfaces, ports and connections.
- **Requirement traceability** – system actions are linked to requirements.
- **Appropriate abstraction level** – models capture essential system characteristics - depth is consistent across packages.
- **Naming conventions** – standardised terminology and casing are used across all packages.
- **Separation of structure and behaviour** – structural definitions and behavioural descriptions are maintained independently.

The DAQ SysML v2 library is organised into eight interrelated packages listed in Table 3, each fulfilling its respective roles while contributing to the integrity of a system-of-systems architecture. All packages are open-source and available inside a Git repository prepared for demonstration purposes: <https://github.com/Ramosa5/PSC-Data-Acquisition-System>. They are not an integral part of HEALIOS mission and can be modified or extended freely after forking the repository.

```

1 package Initialisation {
2   private import ISQ::*;
3   private import ScalarValues::*;
4   private import PayloadActions::*;
5   private import PhotovoltaicModule::*;
6   private import Components::*;
7
8   part PVModule : PhotovoltaicModule::PVModule;
9   part DAQ : DataAcquisitionModule::DAQModule;
10
11   part Payload {
12     ref part DAQ : DataAcquisitionModule::DAQModule;
13     ref part PVModule : PhotovoltaicModule::PVModule;
14     state PayloadMode : SatelliteMode;
15
16   part HEALIOS_Mission {
17     ref part Payload;
18   }
19 }

```

Listing 1: High-level initialisation code

The initialisation package creates a sandbox environment and is intended to be used for testing other packages and their usage. The high-level mission model is listed as code in Listing 1. It contains the main modules modelled as parts. The level of abstraction can be modified by invoking parts definition until the desired level of detail is achieved. It is advisable to leave the parts at a uniform depth. That way, the parts can be visualised with their ports at any point. The model stays predictable and legible.

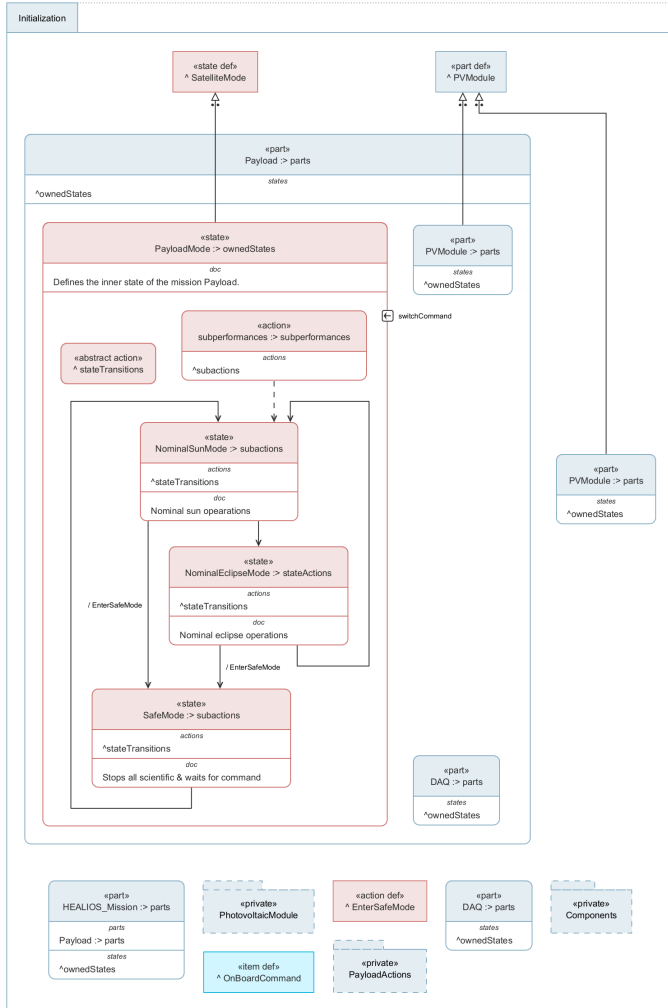


Fig. 5: Initialisation code visualisation.

Furthermore, defined packages and their structures can be visualised, making them easier to interpret. A system model implemented this way can be understood by both engineers and non-technical stakeholders. Another advantage of the SysML v2 implementation is the model’s machine translation. Written code can be interpreted using dedicated code interpreters such as the used Syside Modeler [16]. An example visualisation is shown in Fig. 5. Mission mode logical diagram is implemented as a state machine. Each state is a defined mission mode with documentation.

B. Resulting System Hardware

Payload hardware design is a direct result of the stated architectural decisions and the requirements set. A Model-based framework helps define and document those results and creates a dedicated sandbox for the engineering part. The hardware resembles the modular distribution and defines the relation between the photovoltaic module and the DAQ module. The composition of the system was arranged iteratively, with several elements contributing to the whole design.

Photovoltaic elements that belong to the Payload are electrically decoupled from the EPS and do not power any satellite circuitry. Their power is negligible compared to the satellite’s total power consumption and therefore cannot be considered reliable. However, as the photovoltaic elements still generate electrical power, a way to dissipate it must be provided. Power dumping resistors have been used as a simple load for the Payload’s photovoltaic elements. Special radiators are considered sufficient to dissipate heat and protect the spacecraft from overheating in this area. All electrical power used by Payload comes from EPS and is transferred via 3.3V and 5V power lines. All electrical lines providing power are thus considered part of the EPS. The Payload reconditions them locally through a dedicated filtering stage to generate filtered internal rails. This local isolation is essential for precision photovoltaic measurements, because it protects the sensing chain from switching noise and bus disturbances originating elsewhere in the spacecraft. Fig. 6 shows that Payload is also dependent on the On-Board Data Handling System. Data gathered by Payload is acknowledged and sent to that system via a serial bus. The frequency of sending data is set by the OBDH. Payload’s MCU receives commands about mode selection and manages them.

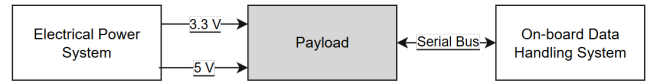


Fig. 6: System-level Payload connections.

Fig. 7 presents the functional architecture of the HEALIOS Payload, divided into modules. This partition reflects the physical and functional separation adopted in the Payload design. A photovoltaic module has three types of solar cells. Each of them is connected to its own MPPT unit. Solar cells are also connected to the I-V sweep and reverse bias logical lock. That way, full current-voltage and characteristics of the cells can be gathered. During Nominal Eclipse Mode, only the PSCs tagged as self-healing would interact with this circuitry when voltage is applied.

The other part of the architecture is the DAQ module, which serves as the electrical and logical interface between the experimental solar cells and the spacecraft data system. The first functional block within the DAQ module is the set of MPPT units, which are responsible for

maintaining the photovoltaic samples near their maximum power operating point during illuminated orbital phases. This enables continuous tracking of $P_{MAX}(t)$ and provides representative information on the real operating capability of each cell type. In parallel, the I–V sweep and reverse-bias circuitry provide two additional functions essential to the mission’s scientific objectives. First, it enables controlled acquisition of full current–voltage characteristics for selected samples, allowing the extraction of key parameters such as V_{OC} , I_{SC} , and calculation of fill factor, and maximum power. Second, during the eclipse, the same circuitry applies a controlled reverse-bias stimulus to the designated perovskite group to trigger self-healing through controlled reverse bias. At the centre of the DAQ module is the MCU, which coordinates Payload operation, mode transitions, and measurement sequencing. This element is connected to the OBC via the data interface.

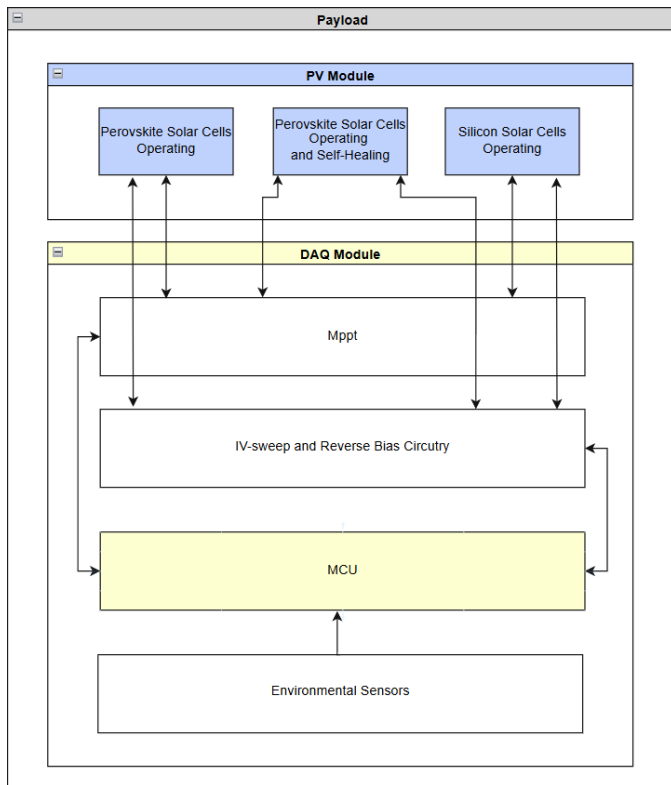


Fig. 7: Functional architecture of the HEALIOS Payload.

The Environmental Sensors functional block visible in Fig. 7 consists of 4 main sensing elements. The temperature sensor, photodiode, and spectrometer have to be placed on the satellite surface, possibly close to the solar cells. The fourth element is used to measure radiation dose. It can be placed inside the spacecraft, as the measured radiation dose is expected to be sufficiently representative of the surrounding space environment. Samples can be gathered with a frequency of 1 Hz or 10 Hz, controlled by the MCU of the DAQ module. Notably, the exact rates are to be determined in future iterations.

C. MPPT, I–V Sweep and Reverse-Bias Circuitry

As the main interest lies in the solar cell coupons, the primary interface between the photovoltaic module and the DAQ module is the two electrodes mounted at both ends of the coupons. They are connected via electrically isolated routes to other system components. This design allows for \pm voltage application and power harvesting.

In HEALIOS Payload, the MPPT function is not used as a conventional spacecraft power-interface block, but acts as a controlled electronic load that keeps each photovoltaic coupon at its instantaneous maximum-power operating point. Degradation tracking is used together with V_{OC} , I_{SC} , fill factor, and derived I–V curves. Second, the maximum-power point of a solar cell is not fixed; it shifts with irradiance, temperature, and ageing, so a static resistive load would not provide a representative measure of real in-orbit operating behaviour. By continuously forcing operation near V_{MPP} , the DAQ captures the quantity most relevant to practical power generation while still keeping the Payload electrically decoupled from the EPS. Hence, it maintains consistent electrical stress on the PSCs and prevents the experiment from perturbing the spacecraft’s power budget.

To allow both MPP tracking and reconstruction of voltage–current curves, the Payload switches between MPPT and I–V curve measurement once per orbit during the Nominal Sun Mode. In the HEALIOS mission, the duration of this mode is predicted to be around 82 minutes, provided it is not interrupted by unpredictable conditions that would turn the satellite into Safe Mode. This allows regular scheduling of the measurement, which is designed to be taken 10 times per orbit, once every 8 minutes. Throughout this process, MPPT units are not in control of the solar cells and turn back on after a full electrical characteristic curve is obtained. Moreover, channel switching is performed only between measurement sequences, and sufficient settling time is allocated after each transition to ensure stable operating conditions prior to data acquisition.

During the Nominal Eclipse Phase, a single row of PSCs is reverse-biased at -0.5 V for the whole phase duration of approximately 10 minutes. It is a value which lies well within the safe operating regime and has been tested under laboratory conditions [6]. It is important to state that if the reverse bias becomes too deep or too long, the mechanism changes: reverse current rises, local dissipation increases, and the cell can enter the regime of irreversible shunting, dark-spot formation, or even electrochemical decomposition. Degradation under reverse bias is reported to remain stable up to around -5 V, whereas below -5 V the process becomes unstable, with the onset of strong current fluctuations and non-uniform degradation mechanisms. At even higher reverse bias (below -10 V), catastrophic failure can occur [17]. For this reason, HEALIOS Payload treats reverse bias as a tightly bound recovery stimulus.

For detailed electrical characterisation and eclipse recovery experiments, the Payload uses a shared precision measurement branch that can be connected to any photovoltaic coupon through a protected channel-selection stage. Each coupon is treated as a floating two-terminal device and is associated either with its nominal MPPT branch or with the characterisation branch. Routing logic from the photovoltaic element perspective is shown in Fig. 8. The latter is built around a digital-to-analogue converter, a control amplifier, a MOSFET-based programmable load stage, and a precision shunt resistor. In nominal polarity, this circuit performs stepped I–V sweeps by varying the electrical load applied to the photovoltaic coupon and measuring the resulting voltage and current. For self-healing experiments, a polarity-selection stage reverses the coupon connection with respect to the programmable source/sink block, thereby enabling controlled, current-limited reverse-bias operation using the same precision measurement hardware. This solution minimizes hardware duplication, preserves measurement repeatability, and ensures strict electrical isolation between the experimental coupons and the spacecraft power bus.

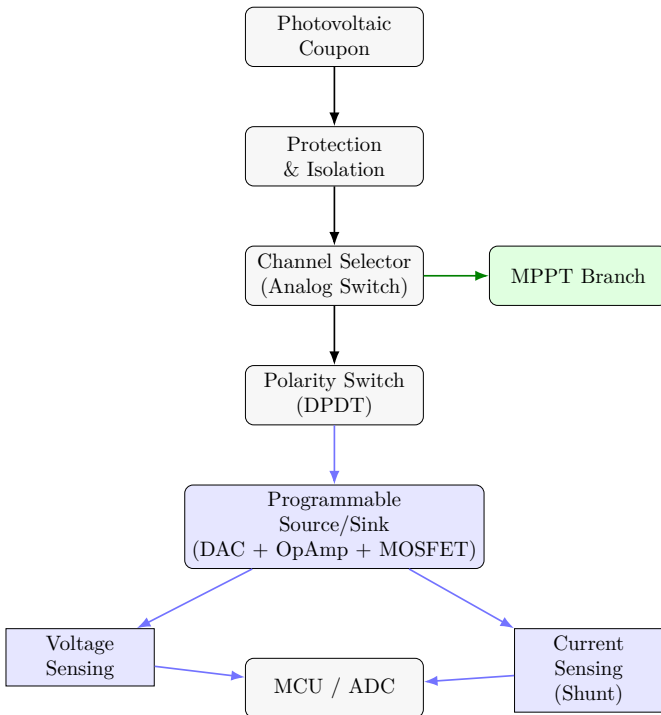


Fig. 8: Functional architecture of the shared I–V sweep and reverse-bias branch from solar cell coupon perspective.

The switching network and programmable load are controlled by the MCU through digital control inputs. The MCU configures the channel selection, polarity switching, and DAC output, thereby defining the operating mode. Importantly, the control circuitry is electrically separated from the analogue measurement path to minimise noise coupling and preserve measurement accuracy.

D. Interfaces and Mounting with External Plate

The Payload distinguishes two main interfaces. The inner electrical interface and the outer mechanical interface. The first one provides a direct connection between the DAQ module and the photovoltaic module. The latter is a physical nesting element that establishes a flow of data from the environment to the system.

The electrical interface is realised through a dedicated harness assembly connecting the external elements to the internal DAQ module PCB. The harness carries the two-terminal photovoltaic coupon lines, sensor supply and signal lines, and low-level analogue measurement signals. Since the photovoltaic elements alongside environmental sensors are mounted externally while the electronics are located inside the spacecraft PCB stack, the interface is implemented using routed cable bundles terminated by board-to-wire connectors at both ends. Each photovoltaic coupon is connected through an individual pair of conductors, corresponding to its positive and negative electrodes.

The harness is thus functionally divided into three groups: photovoltaic coupon lines, environmental sensor lines, and auxiliary supply/control lines. To maintain measurement reliability, the photovoltaic measurement lines are routed away from high-current EPS conductors and switching electronics. The shielding strategy uses twisted, shielded signal pairs for low-level photovoltaic and sensor lines, with the shield grounded at the DAQ side.

The mechanical interface is an external mounting plate layout, which hosts all Payload components that require direct exposure to the space environment. The spatial distribution of these elements on the outer layer is illustrated in Fig. 9. The plate is mounted on the spacecraft face, nominally oriented toward the Sun. Within the HEALIOS mission architecture, this face is also aligned with deployable solar panels on adjacent sides, ensuring optimal illumination and efficient use of the available surface area.

The mounting plate follows the standard 1U CubeSat form factor, with overall dimensions of 10×10 cm. It serves as the primary interface between the space environment and the experimental Payload, supporting photovoltaic samples and environmental sensing elements. To enhance stability and survivability under launch loads, the components are partially recessed into the plate structure.

The photovoltaic section is organised into three horizontal rows. The two upper rows are dedicated to perovskite solar cell coupons. Each is comprised of four rectangular plates with dimensions in the range of 1.5–2.0 cm. Each row contains four such plates, with four individual cells per plate, resulting in a total of 16 PSCs per row. This arrangement allows parallel testing of multiple samples under identical environmental conditions, enabling meaningful analysis even with partial Payload loss. The lowest row contains reference silicon solar cells, implemented as custom-shaped plates designed to match the effective active area of a single PSC row.



Fig. 9: 3D render of the photovoltaic mounting plate.

Environmental sensing elements are centrally positioned within the layout to ensure representative measurements of the local conditions experienced by the photovoltaic devices. Two compact sensors—a photodiode for irradiance monitoring and a temperature sensor—are symmetrically positioned near the plate’s geometric centre. Additionally, a spectrometer is located in the lower central region, represented by a white rectangular piece in Fig. 9. The angle of incidence is constantly measured, even though it is mostly valid in the initial mode change from Nominal Eclipse to Nominal Sun when the satellite is freely rotated.

The uppermost section of the plate is occupied by a regular solar panel connected directly to the EPS. It is therefore not part of the experimental Payload. Although this imposes constraints on available space, it significantly improves overall power-generation capability. Finally, the design incorporates structural features required for integration with the CubeSat platform. Dedicated rail interface regions are included to comply with standard deployment mechanisms, while mounting holes located at each corner provide secure attachment points. The presented plate will be designed and manufactured by the HEALIOS team. The project is currently at too early a stage of development to provide definitive component spacing and detailed interface definitions. Nonetheless, the component list and conceptual design are provided and are currently being analysed in coordination with the responsible subsystem teams.

V. CONCLUSION AND FUTURE WORK

The HEALIOS mission is a 1U CubeSat developed by students from two universities. The central objective of the project is to validate the self-healing properties of perovskite solar cells in a space environment. Promising terrestrial laboratory results will be tested in Low Earth Orbit, with shorter, more frequent operational cycles, temperature fluctuations, and the effects of vacuum and microgravity. The experiment involves applying a controlled reverse-bias voltage (-0.5 V) to a specific set of PSCs during the eclipse phase. Terrestrial studies suggest this induces defect passivation (self-healing).

The Payload consists of two functionally integrated modules: a PV module (silicon and perovskite solar cells) and a DAQ module (electronics for evaluating experimental performance and data collection). Over the 12-month mission, the Payload records electrical parameters, specifically open-circuit voltage, short-circuit current, and maximum power output, as well as environmental data (e.g., temperature or angle of incidence). These characteristics allow the team to quantify the degradation and healing rates for comparison with standard solar cells and with perovskite solar cells not subjected to the self-healing procedure. The acquired data will be processed into structured datasets and thus will enable future studies by providing a reference for the analysis of perovskite solar cell degradation and recovery under orbital conditions.

As students fully develop the HEALIOS mission, the project is susceptible to fragmented development processes, limited requirement traceability, and system-level design gaps typical of such missions. Consequently, the development of the Payload shifted from a document-centric to a model-centric design. The selected packages are open-source and available in a repository: <https://github.com/Ramosa5/PSC-Data-Acquisition-System>. The full system repository is under development, while the one presented is tailored to the article.

As of early 2026, the HEALIOS mission is progressing through Phase B. Consequently, the system architectures, hardware diagrams, and analyses presented in this paper serve primarily as preliminary design or feasibility study documentation, rather than procurement or manufacturing documentation. Consequently, the Payload team focuses on maturing these conceptual models to start purchasing components and preparing for assembly.

Future iterations will focus on the physical implementation of the Payload electronics. In parallel, the SysML v2 model will be extended with lower-level hardware definitions, packet structures, and verification cases. The model can therefore evolve from a descriptive system representation into a practical tool for integration and verification. In the longer term, the concept may be reused for other CubeSat-based photovoltaic or material-degradation experiments, including different photovoltaic technologies or alternative biasing protocols.

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